

Cryogenic Polarization Chopper for Millimeter and Sub-Millimeter Waves

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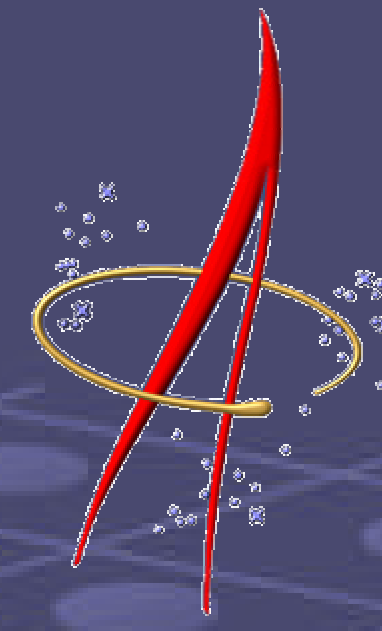
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Acknowledgements

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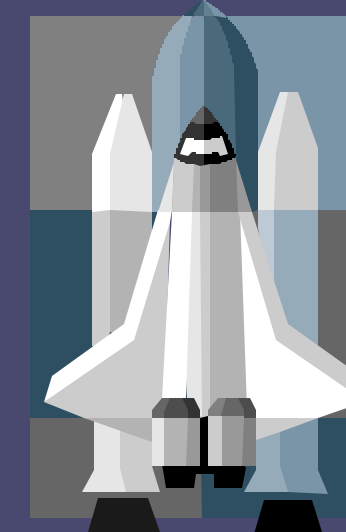
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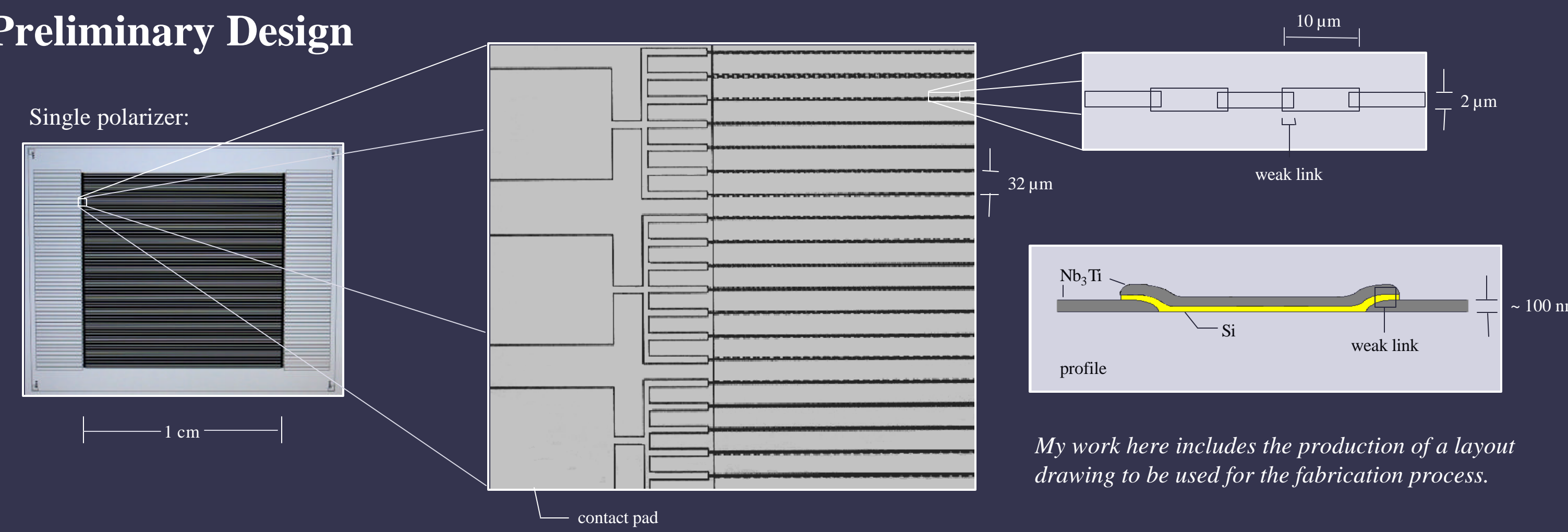


Abstract: The polarization of the Cosmic Microwave Background (CMB) is perhaps the only photon diagnostic of the pre-inflationary Universe. Studying the polarization exhibited by CMB anisotropies can provide information on primordial gravitational waves and on the epoch of a secondary reionization, as well as further knowledge of primordial temperature anisotropies. We are developing optical components to modulate polarized millimeter and sub-millimeter wavelengths in the hopes of detecting these weak polarization signals from the CMB. Unlike conventional optical modulators, these optical components have no moving parts and are compatible with cryogenic detectors such as those for NASA's planned Inflation Probe mission.

Description of the Chopper:

- Two linear polarizers with orthogonal transmission axes
- Cryogenic chopper with no moving parts achievable with “weak links”
 - Weak links sufficient but possibly not required; however, we believe that weak links result in lower power dissipation than other solutions
- Superconductive Nb₃Ti: Critical temperature (T_C) ~ 10 K
- Each polarizer will switch between two states (on/off)
- “On” and “off” states correspond to superconducting and normal states
 - Device will operate below T_C
 - Normal state achieved by applying a current $I > I_C$ (Silsbee effect)
- Differential signal between transmitted polarizations can be obtained

Preliminary Design



My work here includes the production of a layout drawing to be used for the fabrication process.

Behavior of Weak Links:

Superconductor-insulator-superconductor (SIS) junction during superconducting mode:

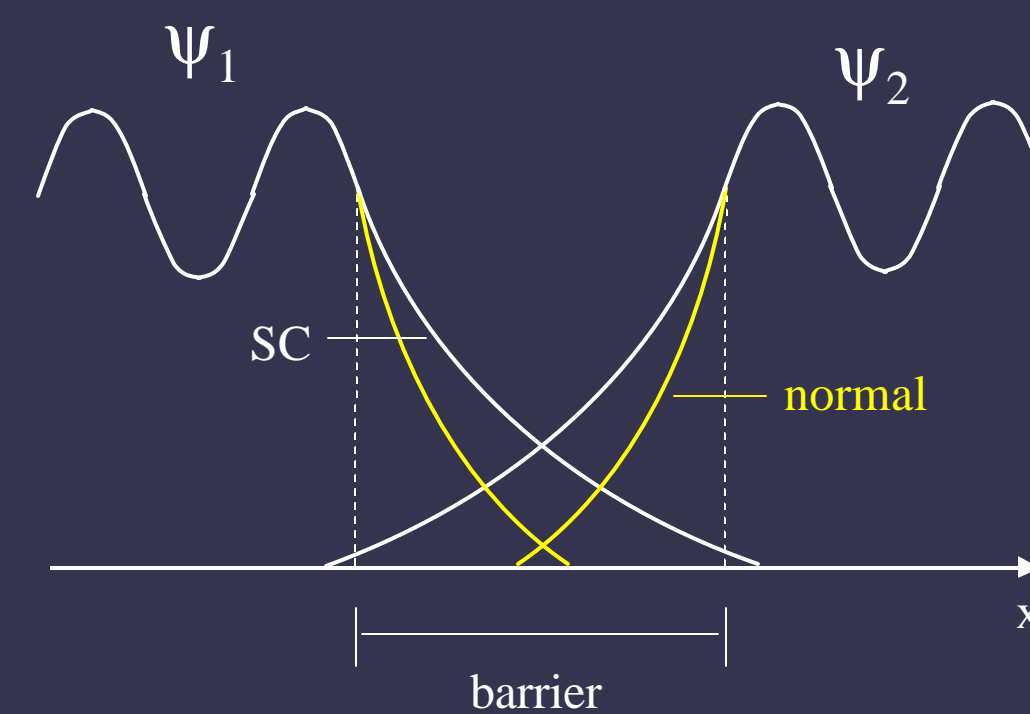
- Thickness of insulating barrier must be less than coherence length, χ_0 , of Cooper pair
- DC Josephson effect: Supercurrent of pairs via quantum-mechanical tunneling
- Junction has minimal effect on superconductivity
- Material behaves as perfect conductor when $E_{\text{photon}} = hc/\lambda < 2\Delta \rightarrow$ high reflection of incident photons

Normal-insulator-normal (NIN) junction during normal mode:

- Lower tunneling probability; voltage drop across junction
- Junction creates large resistance between respective wire fragments
 - No coupling of radiation when $L_{\text{fragment}} \ll \lambda_{\text{photon}}$
 - Material behaves as dielectric \rightarrow high transmission of incident photons

The weak links allow tuning of I_C and R_{eff} of the wire with the junction thickness, resulting in greater engineering capabilities. They also help to reduce Joule heating in the system which is more compatible with cryogenic detectors.

Tunneling at Junctions

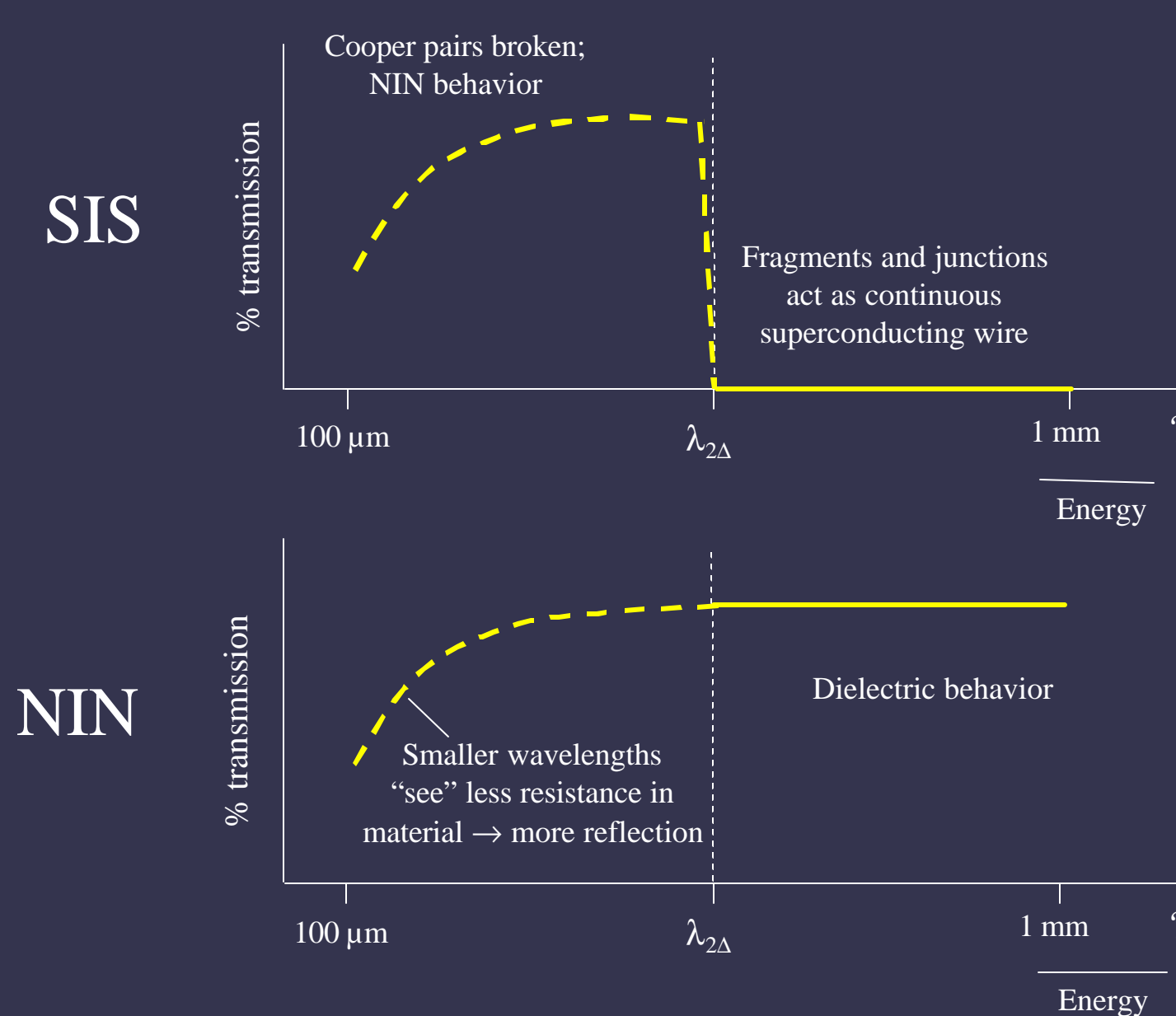


If the SC wave functions overlap, the superconductors separated by insulating barriers can lock phase creating a SC wire. Increasing current causes dephasing at interfaces. When I_C of a junction is exceeded, a resistance is created.

Coherent wave functions in superconducting state can penetrate deeper into barrier, whereas non-Cooper pair electrons experience greater scattering.

Ideal Transmission of Light with Polarization Parallel to Wire

A simple switch of resistive state gives a large response in effective transmission!

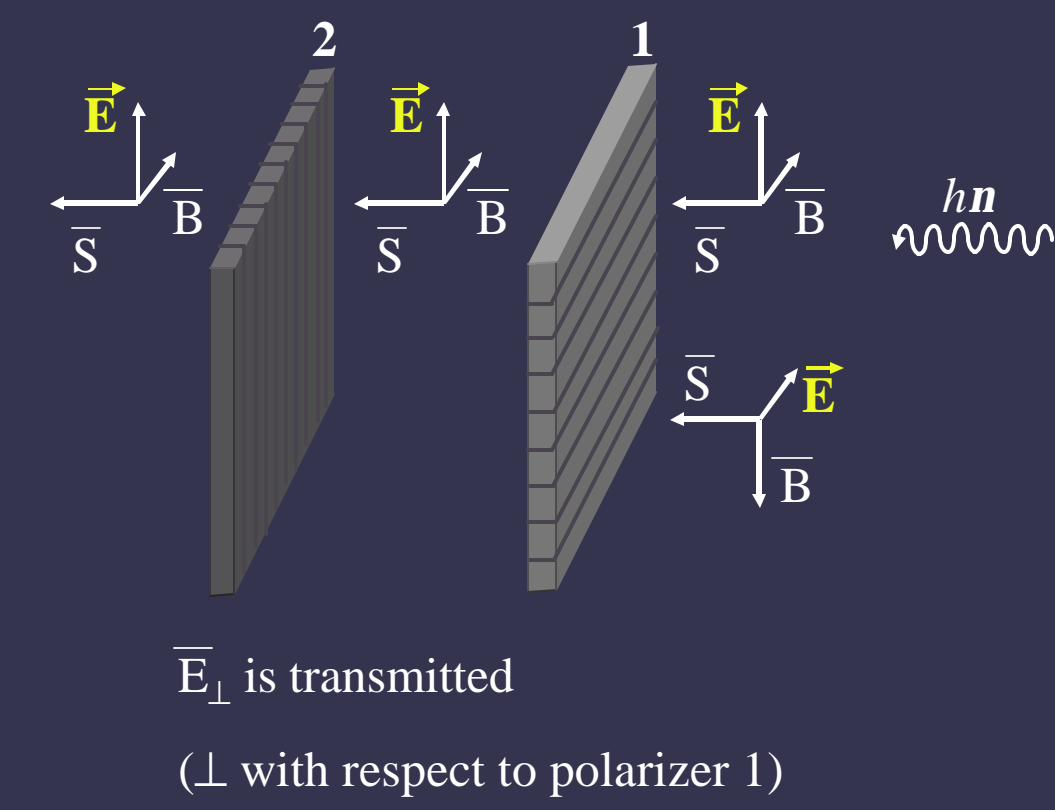


Binding energy of Cooper pair when $T \ll T_C \sim 2\Delta = 3.51k_B T_C$
This energy corresponds to $\lambda = 410 \mu\text{m}$ for $T_C = 10 \text{ K}$

Light polarized perpendicular to wires: Full transmission in both states when wavelength is larger than width of wire.

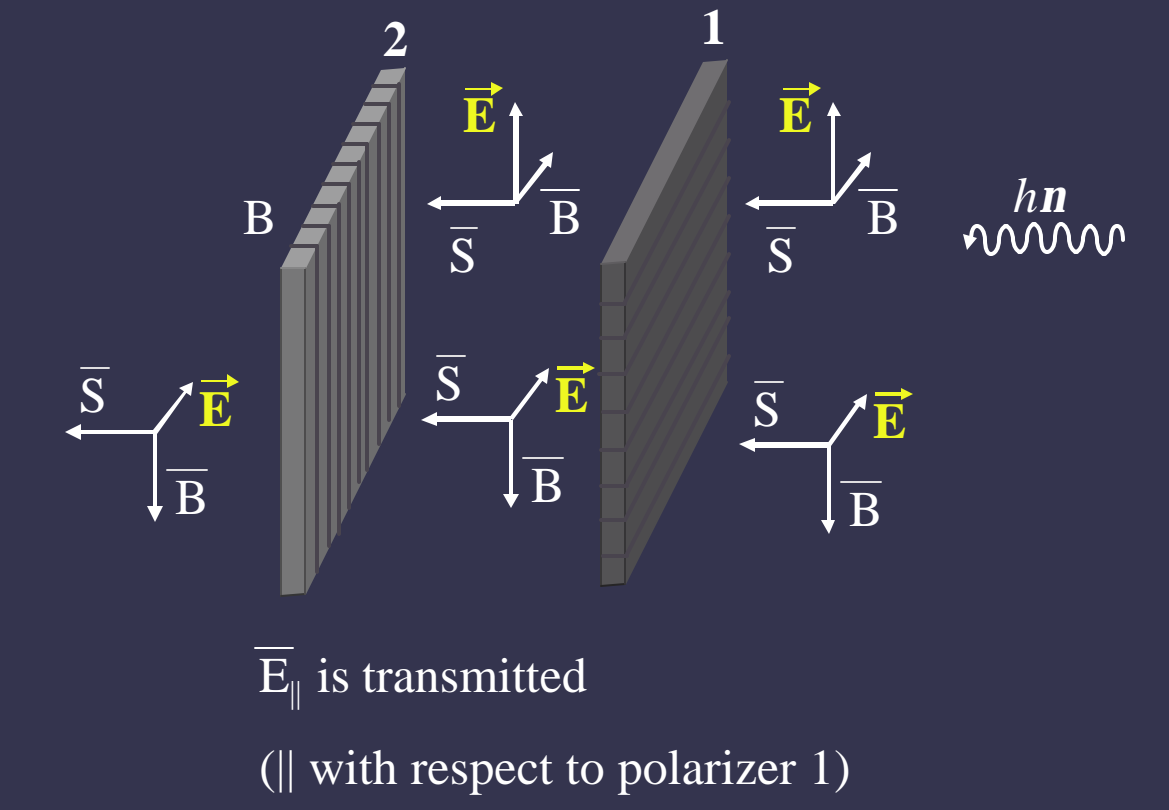
Expected Transmission of Polarizations through Chopper for $\lambda \sim 1 \text{ mm}$

Mode 1:



\vec{E}_\perp is transmitted
(\perp with respect to polarizer 1)

Mode 2:



\vec{E}_\parallel is transmitted
(\parallel with respect to polarizer 1)

This device will successively switch between modes, transmitting one polarization at a time. The differential signal between two orthogonal polarizations can be obtained by subtracting one from the other.

Poynting vector:

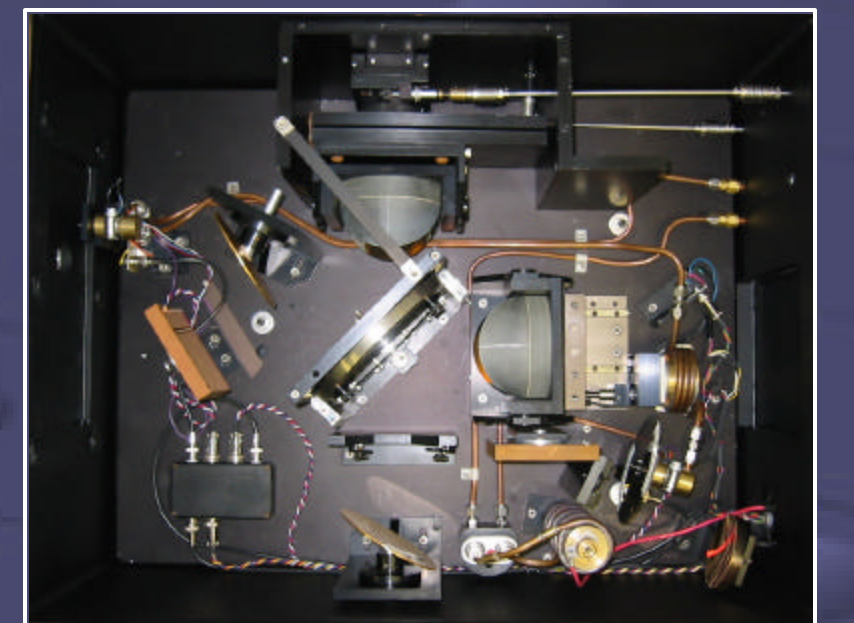
$$\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B}$$

SC

N

Short-term Goals:

- Determine the optimal film thickness, d
 - The requirements are a high enough T_C ($> 4.2 \text{ K}$) and a high resistivity, r , when normal
 - Smaller thicknesses yield larger resistances: $d \sim r^{-1}$
 - T_C can be suppressed with film thickness
 - Find $r(d, T)$ and $T_C(d)$ down to 4K using four-terminal measurement technique
- Determine the optimal weak link thickness, a
 - Compromise: Need thin barrier for greater SIS junction tunneling, though this necessitates a larger I_C
 - Measure $I_C(a)$
- Specifications are now complete; chopper is ready for fabrication
- Test transmission of light in normal and superconducting states
 - Fourier Transform Spectrometer (FTS), bolometer, and dewar
 - Test at various temperatures from 4K \rightarrow 1K

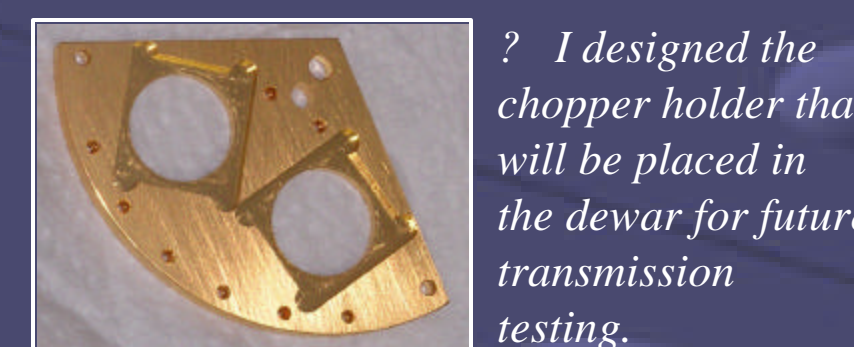


FTS



DT-470 Thermometer

Dewar



? I designed the chopper holder that will be placed in the dewar for future transmission testing.

Current Results:

| d [nm] | T_C [K] | R_{eff} [W/?] $T \sim 298 \text{ K}$ | R_{eff} [W/?] $T \sim 10 \text{ K}$ | x [nm] |
|----------|-----------|--|---|----------|
| 47.6 | 7.50 | 31.5 | 28.5 | 12.5 |
| 58.6 | 9.18 | 41.2 | 31.4 | 9.67 |
| 95.23 | 8.22 | 14.2 | 11.4 | 13.3 |
| 127 | 9.90 | 12.1 | 8.55 | 12.1 |

Effective coherence length: $\chi = \lambda_0 \mu_{\text{mlp}}^{-1/2}$
 μ_{mlp} : Mean free path computed by Drude model

